The Learning Brain, the Learning Individual, the Learning Organisation

Proposal for an interdisciplinary research programme on learning processes

1. Purpose of the report

1.1 General

In the summer of 2001, the Swedish Foundation for Strategic Research decided to initiate an investigation for a possible interdisciplinary research programme on learning processes and asked Professor Peter Gärdenfors to head it. He formed a steering group and applied for additional funding. The work has been generously financed by the Swedish Foundation for Strategic Research, the Bank of Sweden Tercentenary Foundation, the Committee for Educational Science of the Swedish Research Council and the Knowledge Foundation.

The steering group has included:

Professor Peter Gärdenfors, Cognitive Science, Lund University, Chair

Professor Roland S Johansson, Integrative Medical Biology, Umeå University

Professor Anders Lansner, Numerical Analysis and Computer Science, Royal Technical Institute

Professor Roger Säljö, Department of Education, Göteborg University

Professor Arne Öhman, Clinical Neuroscience, Karolinska Institutet

Dr. Olle Edqvist, Swedish Foundation for Strategic Research.

B.A. Maria Larsson, Cognitive Science, Lund University, has served as the secretary of the group and as the coordinator for conferences and workshops.

The activities of the steering group have been three-pronged: (1) we have organised a series of international workshops; (2) we have commissioned four research overviews on sub-areas of the domain of learning processes; and (3) we have collected research proposals and ideas from a large number of Swedish researchers and research groups in the area. The programme initiative will be concluded by a seminar on June 2, 2004, reporting on the results of the investigation.

1.2 Objective

The purpose of this report is, based on the work done over the past two years, to propose an interdisciplinary research programme on learning processes. The aim of the programme is to develop Swedish research in this area, widen its scope and improve its quality. Our ambition is also to further internationalise Swedish research in this area on the assumption that collaboration with research groups abroad will often be needed to facilitate and stimulate the research,

As an underlying rationale for our proposal, we consider that the long-term goal of the research on learning processes should be to generate results that can:

i) stimulate research and support policy recommendation of relevance for education and learning in a life-long perspective and on the individual as well as the organisational levels;

ii) provide background knowledge for the development of educational as well as technical systems for the disabled;

iii) provide background knowledge for the design of adaptive man-machine interfaces;

iv) provide inspiration for the design of technology based on learning research;

v) help prevention and treatment of learnt destructive social behaviour e.g. fobia, drug abuse, criminality;

vi) help understand the influence of media, advertising etc on different groups and the consequences of media changes for learning in institutional settings such as schools and universities;

vii) contribute to the discussion of issues of learning in the modern democratic society where knowledge and skills play an increasing role for the individual as well as for organisations.

The primary aim of this report is to identify research that can contribute to these goals. The focus will be on interdisciplinary research that may be difficult to finance from regular sources. We will also indicate the practical relevance of the research, in particular in relation to what it can say about how different kinds of learning are best supported.

1.3 Summary of our proposal

This report concludes that funding should be prioritised for the following five areas, where one finds a substantial Swedish competence and promises for successful research.

- Synaptic, cellular and neuronal network mechanisms of learning and memory
- The role of emotion and motivation in learning and memory
- Concept formation and conceptual development
- Intersubjectivity and dialogue in contexts of teaching and learning
- Computational modelling (runs across all four themes above)

We argue that it is important to establish interdisciplinary bridges that can connect islands of knowledge from different scientific fields.[1]

The material that follows will broadly describe research in the different areas of learning and provide the motivation for focussing on the four proposed areas.

The following attachments include supplementary material to the contents of this report:

1. The programme for this study as set out when it was initiated.
2. Andreas Olsson's report on emotion and learning.
3. Anders Sandberg's report on computational models of memory and learning.

[1] Cf. Isaac Newton: "Men build too many walls and not enough bridges."

4. Maria Larsson's *Lärkraft* on IT and learning (commissioned by the Knowledge Foundation).
5. Åsa Harvard's report on play and learning.
6. The introductory chapter by Petter Johansson and Peter Gärdenfors to the volume *Cognition, Education and Communication Technology* (based on a conference financed by the Bank of Sweden Tercentenary Foundation).
7. The set of one-page research proposals from Swedish scientists/research groups in response to our questionnaire.
8. The programmes for the series of workshops that we have arranged.

2. What is learning?

We find learning processes in many types of systems and on many levels. The main sources of knowledge about learning include:

- Human psychology and neuropsychology
- Psychological experiments with animals
- Experimental neuroscience with animal models
- Computational models
- Educational research and practices
- Knowledge production and reproduction in organisations

One fundamental problem when discussing and studying learning processes is that the concept "learning" is used in a multitude of ways. The notion of learning is applied to a wide variety of entities: neurons, neuronal assemblies, brains, individuals, groups, organisations, societies, algorithms, machines, etc. So a first problem to be addressed is to delineate roughly some meaningful conceptual spheres within which it makes good sense to expect knowledge from different areas of research to interact and fertilize each other, and to separate these from other, more distant areas, where such interaction cannot be expected.

It is futile to hope that one can find a characterisation of "learning" that can be applied to systems on all levels: we use the same word for completely different processes and we will have to keep the process in mind or risk being confused in our analysis of learning. In order to make the concept of learning substantial, we have to specify it by grounding it in a conceptual framework and/or in specific contexts.

Learning is a complex of different capacities and also closely tied to processes of memory formation. Even if one focuses on individual learning, there are many kinds of learning. Some are related to bodily practices: we learn to walk, to ride a bike and to tie our shoelaces. Some are related to concept formation tasks that we need for everyday problem solving: we learn to distinguish edible mushrooms from poisonous ones, to recognize relevant icons on toilet doors and to tell a false smile from a friendly one. Some kinds of learning are part of culture and education: we learn to count, we learn the months of the year, the stomachs of the cow, the countries of Asia, and the history of the world wars. And we learn languages; the one(s) of our early years quite painlessly, later ones only with great effort and without complete success.

The traditional definition of learning in cognitive psychology is: *A change in an organism's capacities or behaviour brought about by experience*. The first thing to note is that this definition is framed in terms of behaviours does not explicitly mention

neural processes and cognitive components. And as already the examples above show, it is too narrow since it fails to reflect many forms of learning.

In contrast, if one looks at how encyclopaedias define learning, one finds a welter of aspects that are connected with learning. To give but one example, the *MIT Encyclopedia of Cognitive Science* mentions the following: conditioning, skill learning, memory generation, forming cognitive maps, induction, deductive reasoning, forming schematic knowledge, categorisation, analogy formation, language acquisition, and imitation learning.[2]

The definition is also too broad, since increase in muscular strength brought about through exercise or even decrease by an illness may satisfy the definition. And then, if learning in a single neuron and complexes of neurons are included, one finds further forms of learning, such as Hebbian learning resulting in changed synaptic connections between neurons. Finally, if one widens the horizon to learning in organisations, still further aspects of learning become relevant, like new organizational knowledge, new patterns of organisation, routines or work processes.

One could try to broaden the traditional definition and argue that learning is a change in a system's (neuron, individual or organisation) capacities or behaviour brought about by experience. But this broadened definition would suffer from even more severe drawbacks than it does for individual learning.

We must therefore conclude that at present there is no conceptual framework, much less a theory, that can account for all the varieties of learning. The dream of behaviourism was that all learning could be explained in terms of associations between stimuli and responses, where the relevant mechanisms were different kinds of conditioning. However, it soon turned out that conditioning could not even explain much of the learning mechanisms of rats, the favourite animals in the studies. Their searching behaviour is best explained if it is assumed that the rats have the ability to follow some form of "cognitive maps." And as regards language learning, Chomsky's devastating criticism of Skinner's theory shows that there is more to the mastery of language than stimuli and responses.

The upshot is that already when it comes to understanding what we mean by learning, much conceptual clearing up is needed concerning the very notion of learning in its different uses. The OECD report *Understanding the Brain*, that will be referred to in section 5, even goes as far as claiming that the "theory of learning is pre-scientific – in the sense that it lacks as yet either predictive or explanatory power. We do not understand sufficiently well how children and adults learn to dare to offer an educational or training guarantee. The science of education is in its Linnaean phase, drawing up lists of examples of successful learning, clarifying and sorting effective teaching practices; but it still awaits its Darwin with a powerful explanatory theory of learning" (p. 10).

On this conceptual level, foundational research is needed that would involve philosophers, psychologists, cognitive scientists, educationalists and organisation theorists, but also researchers in computer modelling and in cognitive neuroscience can contribute by holding forth learning mechanisms that should be

[2]The list looks like the passage from Jorge Luis Borges where he writes that according to a " certain Chinese encyclopedia", animals are divided into "(a) belonging to the Emperor, (b) embalmed, (c) tame, (d) sucking pigs, (e) sirens, (f) fabulous, (g) stray dogs, (h) included in the present classification, (i) frenzied, (j) innumerable, (k) drawn with a very fine camelhair brush, (l) et cetera, (m) having just broken the water pitcher, (n) that from a long way off look like flies".

accounted for. Even though a Darwin of learning cannot be planned for, one can pave the way.

In this report, we view the research area as three interacting or partially overlapping fields: (1) Neuronal studies overlapping with human and animal behavioural studies; (2) human and animal behavioural studies being central and (3) a field based on social studies that overlaps with studies of individual humans. Hence, there is a need to look at individual learning from two different perspectives: the individual brain and its mechanisms of learning; and the individual and his/her learning in social interaction.

3. Key research questions in different research areas

In this central section, the material from all the workshops and reports is summarized. The main objective is to specify a set of key research issues that ought to be addressed and fruitfully might be investigated by Swedish researchers during the next five to ten years. We divide the material into four main sections, each devoted to a central sub-area of research on learning processes.

3.1 The learning brain

3.1.1 Bridging the gap

During the last couple of decades we have seen an explosion of fundamental results in neuroscience. This is one of the currently most rewarding research areas of all scientific fields. Neuroscience is also co-developing with the cognitive sciences, where the former studies the brain from "the inside" and the latter observes it from "the outside". The cognitive sciences study and discover thinking and learning activities. At the intersection of the two fields, cognitive neuroscience generates hypotheses about the underlying mechanisms and studies of those.

However, in spite of the strides in our understanding of he nervous system, one encounters many problems when trying to bridge the gap between the neuroscientific findings and, for example, educational applications. One reason for this, as noted in the OECD report *Understanding the Brain*, is that neuroscientists and educators do not share a common vocabulary or frame of reference. Or if they use the same words, they mean different things – terms like "plasticity," "intelligence" and "stimulation" are examples of this. Another reason is, of course, that one cannot always expect direct links between neuroscience and the complexities of the practices of education, which in itself is a very broad phenomenon involving many different activities and priorities.

Here, the particular focus will be on what neuroscience can contribute to our understanding of learning and memory in humans and its implications for education (once the communication problems have been overcome). But we will also consider its relevance for problems related to ageing and different kinds of disabilities and the role for computational modelling for understanding various kinds of learning processes.

The main reason why neuroscience is potentially important for educational issues is that it can identify some of the basic *mechanisms* for learning, that is, those that are located at a "micro-level." Once we have a good grasp of how these mechanisms work, we will be better able to offer viable knowledge for instance to those who design educational programs and who attempt to remedy specific difficulties in learning capabilities. One of the current main trends in neuroscientific modelling of learning is that the learning mechanism cannot be separated from the *motivational* or *evaluative* aspects of these processes.

3.1.2 Mechanisms of learning and memory

The most recently evolved part of the nervous system, the neocortex, is dedicated to cognition, i.e., to perception, attention, memory, problem solving, planning, and a host of other complex mental acts. Even though plasticity is a characteristic of most neural tissue, there is no doubt that the plasticity of the human neocortex plays of most central role for the staggering plasticity of human behaviour.

The hypothesis that the physiological substrate of memory is enhancement of some of the 10^{14} synaptic connections between neurons in our cortex, i.e. synaptic plasticity, was made popular by Hebb in the late 1940's, but dates back almost a century. Fifty years ago this was one hypothesis among several competing ones. For some time a popular view was that memory was encoded in DNA much as the magnetic tape memory of contemporary computers. The first experimental verification of Hebb's hypothesis came in 1973 when it was shown that synapses in hippocampus did display significant "long-term potentiation" (LTP), i.e. an experience dependent strengthening. Five years later it became evident that these synapses actually followed the rule coined by Hebb stating that "When an axon of cell A is near enough to excite B and repeatedly or persistently takes part in firing it, some growth process or metabolic change takes place in one or both cells such that A's efficiency, as one of the cells firing B, is increased." Such synapses are today called Hebbian synapses.

It has later become evident that synaptic plasticity is a phenomenon which is spread over almost all of the cerebral cortex and that it is also prominent in other brain structures that are important for learning and memory, like the cerebellum and the basal ganglia – key players in motor learning and behaviour selection (decision making). Moreover, many different forms of synaptic plasticity have been described, for instance, synaptic long-term depression (LTD) which complements and counteracts LTP in many systems. LTP and LTD also exist in several different forms, perhaps most notably on a spectrum of different time scales from seconds to days and presumably even years. There are further non-Hebbian forms of plasticity that act at or near the synapses or to modulate the firing tendency of the postsynaptic neuron. Today one finds an almost total consensus in neuroscience (with some very few exceptions) that synaptic plasticity is the physiological substrate behind almost all types of learning and memory. Research to elucidate further the underlying molecular, cellular, and genetic mechanisms is intense.

One particularly interesting kind of plasticity concerns language learning. Research has shown that the later a grammar of a language is learned, the more difficult is the processing for the brain. Instead of processing grammatical information principally with the left hemisphere, late learners process the same information with both hemispheres. This indicates that late learners use a different, presumably less efficient, strategy when processing the language. A consequence of this for educational policies is that learning a second language, in particular when it has a grammar that is different from that of the first language, should take place as early as possible at schools. This example is but one that shows how findings in the neurosciences may have rather direct implication for the organisation of educational practices.

At a macroscopic level, the *hippocampus* at the bottom of the temporal lobe appears critical for the encoding of new declarative memories. For example, animal research demonstrates that semantic and episodic learning is impeded or impossible without a hippocampus. Similarly, bilateral damage to the

hippocampus results in permanent amnesia in humans. Thus, patients with such lesions are stuck in the past, they can converse appropriately in the here and now, but they have forgotten what happened within minutes. Finally, the mechanisms for LTP have been primarily studied on hippocampal neurons. However, the hippocampus is not the site of memory. Rather, it is needed for encoding and consolidating new information in memory, but the long-term information is stored in other cortical areas as well.

It has turned out to be surprisingly hard to make a connection between synaptic plasticity and signs of learning at the behavioural level signs of learning. However, evidence is now accumulating. One key observation that links to important behavioural and even social phenomena is the recently firmly established association between synaptic plasticity and emotional and motivational brain mechanisms. We now know that several of the neuromodulators, such as dopamine and acetylcholine that are released from basal forebrain structures in response to emotional responses, are also potent regulators of synaptic plasticity. Thus, some of the neural processes behind feelings of pleasure and pain act like potent "print-now" signals that gate synaptic plasticity and learning. These brain systems are implicated in many learning and memory disorders and they are also "hijacked" in drug addiction. We are now beginning to understand the details of such important processes, which in turn may open up for improved diagnosis, prevention and treatment.

Theoretical and computational models are today used extensively to describe learning and memory phenomena on different levels, ranging from the microscopic level of biochemical signal processing networks in the synapses to the macroscopic level represented by the dynamics of large-scale neuronal networks. The hypotheses of Hebb have now transformed into highly elaborate, quantitative and experimentally well developed models of learning and memory phenomena. The recently established synergy between experimental and theoretical-computational approaches in brain science is likely to further speed up the advancement of our understanding the behaviour of these highly intricate, complex and non-linear large-scale neuronal networks. This will in the coming decades further penetrate into the cognitive and behavioural brain sciences and establish firm and productive links between neuroscience on the one hand and psychology, psychiatry, and pedagogy on the other.

Research on cellular and mechanisms behind learning and memory is today extensive and focuses on all levels, from the single synapse and its plasticity, over local hippocampal and other cortical networks, to brain imaging studies. Computational modelling is an important component in this research. Such a broad approach is also necessary in order to get a better fundamental understanding of the learning processes of the brain.

Some important research question in connection with this are:

- What is the difference in plasticity between short-term and long-term memory networks and between episodic encoding and encoding that requires repetition? How do the neuromodulatory systems in e.g. the prefrontal cortex and the basal ganglia control plasticity?
- Networks involved in intermediate storage of memory like e.g. the hippocampus have a high plasticity but are also likely to forget fast. Is the memory capacity of these networks in some way limiting in the practical learning situation?

• Classical learning theory has shown that once a connection has been learnt, it can be blocked, but it will appear again under various circumstances. Why is unlearning so difficult? Can bad habits and erroneous knowledge be corrected effectively?

• Which are the sensitive periods in the development of the brain for various skills, for example, language learning? What changes occur in the brain when the learner leaves the sensitive period? Which physiological mechanisms define the sensitive periods and how can those be controlled?

3.1.3 Emotion, motivation and learning

The brain can be understood as a machine devoted to elaborate answers to the question how to find the best way of achieving goals. The overall goals are to a large extent set by evolutionary old neural circuits in brain stem and forebrain structures. The ultimate goal, of course, is what evolution is about: to support the survival by transferring useful genes across generations. In this perspective the more recently evolved neocortex is the control room helping navigating a vehicle that moves genes from one generation to the next (for example by redesigning large scale environments).

The goal-setting sub-cortical brain structures direct neocortical cognition by means of dynamic processes deeply embedded in biological demands. These demands make themselves known as *motivation* and *emotion* at the psychological level. Emotion and motivation are overlapping processes that activate, give direction and persistence to behaviour (Damasio 1994). To the extent that they are differentiated, motivation is seen as emanating from primarily internal processes, such as hunger or need to achieve. Emotion, on the other hand, has its origin in the external world, in stimuli that, for example, provides a threat to wellbeing or a challenge to one's status. From a human perspective these processes make us want to do what our distant forefathers had to do in order to promote the transfer of their genes to new generations. Thus, by substituting a goal-directed state for specific actions, motivation/emotion introduces flexibility between a goal (and derived subgoals) and the means for reaching it.

Emotion and motivation lay the foundation for learning. Primarily this takes place via the processes of reinforcement. A motivational state induced, say, by a temperature imbalance between organism and environment results in the active search for means of restoring the balance. Responses that achieve this goal (e.g., muscle movement to generate heat; seeking shelter; putting on or off clothes; manipulating the air-conditioner) activate the reward system in the brain, which will reinforce the association between the achieved goal and the act that led to it. The reward system is the neural substrate of intense positive feeling, which bears witness that we are designed for learning with joy. The principle of reinforcement does not only hold for stimuli that organisms are designed to approach, but similar principles apply to repellent stimuli that organisms are designed to avoid, such as pain-producing stimuli. Here, it is the termination rather that the presentation of the stimulus that is rewarding. Thus, evolution has designed a mechanism for learning the routes to stimuli that are biologically relevant (for procreation and survival). As a result, the organism learns to expect a particular act to result in a desired goal. In combination with cognitive representation of the emotional valence of available rewards, such expectancies guide action.

The reward system originates from nuclei in the midbrain that signal to the forebrain (the hypothalamus and limbic structures such as the amygdala) that project widely to the prefrontal cortex. This system is activated by all types of

biologically primary stimuli, such as food and drink, sex, affiliative proximity, or the termination of pain. Its neurochemistry is well charted, with dopamine as the most important transmitter. Interestingly, all substances that are known to result in dependency when repeatedly ingested have targets in this system. Thus, the power of addictive substances is that they short-circuit the reward system, mimicking or enhancing the euphoria resulting from stimuli that we like by biological design.

In traditional descriptions of goals for education, the focus has been on how to develop cognitive abilities through reading, writing and mathematics. However, more recent results in psychology and neuroscience confirm what every teacher knows: the emotions of the students are to a large extent responsible for the development of the cognitive skills. The fundamental question is how and to what extent the educational processes can accommodate the nurturing of emotional and motivational competency.

On this topic, the OECD report *Understanding the Brain* writes as follows: "Learning failure occurs when one (or more) of four impediments prevent the achievement of success. These impediments to learning are: a) lack of confidence and self-esteem (the feel-good factor); b) weak motivation (not "really wanting" to learn): c) real (or perceived) inadequate potential ("It's too hard" or "I can't do it"); d) absence of opportunities to learn. Most educational debate addresses the last two, concerning itself with questions like the "ability range", IQ, aptitude – or access, equal opportunities, growth of provision. Important as these issues are, they are not necessarily the major impediments to learning in the developed world today. Concentrating on these almost to the exclusion of the first two was a sort of 20th century heresy. The primary problems for learners are confidence and motivation: this idea, widely shared among educators, could itself provide a fertile field for scientific research." (p. 24)

A related topic concerns the role of delayed gratification for learning. In a longitudinal study four-year old children were first faced with the task of resisting eating one marshmallow placed before them as they were alone in a room in order to get two marshmallows later upon return of the experimenter. The delay of time that the child could resist the urge to eat the first marshmallow was later shown to be strongly correlated with the academic achievements measured by SAT (Scholastic Aptitude Test) scores, task perseverance and concentration.

We are at a stage in which some understanding of emotional phenomena in terms of neural mechanisms is emerging. Thus, it appears a promising strategy to include biological considerations in research programs in which emotion provides a central term even if the focus of the program concerns complex social phenomena or emotional factors in educational settings. However, this done must be done in an interdisciplinary manner to ensure that the complexity of education is not overlooked.

Some promising research questions:

• Although positive emotions are more interesting than negative ones from a general learning perspective, much less effort has been devoted to studying positive emotions such as joy than negative ones such as fear or anger. Demonstrations in animals show that the responses of dopamine neurons in the reward systems can be modified through simple associative learning. These basic findings invites for studies in humans by brain imaging techniques to delineate stimuli that efficiently activate the reward system, and the function of the reward

system in different types of human learning. For example, does evaluative conditioning depend on the reward system?

• Likewise, when participants learn to solve specific types of problems, do successful solutions activate the reward system, and is this activation directly related to the learning of problem solving skills?

• Using different methods to induce positive emotion, it has been demonstrated that participants perform better in a wide variety of tasks, including learning tasks. The question whether happy students learn better than unhappy ones can be addressed at many levels, from basic experiments seeking to delineate neural mechanisms behind the effects of positive mood, to examining relationships between personality traits such as extraversion, mood, and learning, and to looking at the effect of emotional climate in classrooms.

• One general problem of learning concerns what has been called "the premise of equipotentiality", the idea that principles of learning can be formulated independently of the content of what is learned. The alternative idea is that contents count, that there are biological dispositions that tend to channel learning in different directions according to evolutionarily derived rules. Which is the correct one and if biological disposition is critical, which are the most important factors?

• A second general problem of learning that has been studied in a fear conditioning setting concerns *the role of context in learning*. When placed in a specific context in which an animal has been exposed to aversive stimuli, it will show evidence of fear when returned to the context. Recent research suggests that such context learning has a different neural basis than fear elicited by specific stimuli. This asymmetry between conditioning and extinction has interesting implications for the treatment of fear and anxiety, but so far it has been studied to a very limited degree in humans. For example, it suggests that changing emotions in the context of psychotherapy may be specific to that very context and not generalize to real life settings unless special efforts are taken to promote generalization by testing therapeutic effects in new settings.

• The discovery of so called "mirror neurons" in the primate brain has generated considerable excitement. These are neurons that fire not only when subjects perform a particular act but also when they see this act performed by a companion. Apart from providing a mechanism for understanding actions by others, these neurons may form the basis for the proclivity of primates to imitate each other and for *learning by imitation*. Humans are sensitive to the emotional expressions of others and it is likely that a good deal of our everyday understanding of emotional phenomena derive from observing and imitating the emotional gestures of others.

3.1.4 Learning of skills and re-learning after neural injury

Peripheral as well as central nerve injuries are extremely common causes for disabilities. For example, some 80.000 Swedes suffer each year from peripheral nerve injuries and some 30.000 from stroke resulting in chronic nerve injuries. Importantly, any recovery from neural injury in the chronic stage requires re-learning, where still functioning neuronal networks partly compensate for tasks that critically depended on the injured neural tissues, whether peripheral or central. Furthermore, re-learning by the brain will be required regardless of primary therapeutic approach. Therefore, understanding the mechanisms that account for learning is critical for optimizing recovery from neural injury. Indeed,

neurorehabilitation currently undergoes a paradigm shift driven by the increased understanding of brain functions and their plastic reorganization after training or injury.

By combining behavioural, physiological and brain-imaging techniques for studying sensori-motor functions involved in learning and control of motor skills, we gain considerable amount of new knowledge regarding novel and more efficient rehabilitation programs. For example, functional magnetic resonance imaging (fMRI) and trans-cranial magnetic brain stimulation (TMS) can depict brain areas and networks engaged in performing relevant tasks and also how brain activities change with skill learning and re-learning. A depiction of regional changes in individual brains as a function of learning success should help us understand why individuals fail to learn or re-learn after injury, and how one might promote learning and re-learning both on a cognitive and a biological level.

With the current development of novel cellular and molecular-genetic approaches for primary therapy, it becomes increasingly clear that re-learning of the CNS will become a limiting factor in achieving functional restitution after neuronal injury. For example, during nerve regeneration, several factors may lead to misdirection of the growing fibers, reaching targets different from the prelesional ones and thus blur the original topography. Likewise, the properties of those synaptic connections that may be (re)established will differ.

Ultimately, the underlying neural mechanisms supporting post-lesion recovery are those that mediate learning and memory in neural networks, which include mechanisms that govern changes in synaptic efficacies, synapse formation and elimination as well as survival and differentiation of neurons.

As such, skill learning grows directly out of motor control processes that operate in egocentric spatial frames and outside of awareness: (1) the *perceptual motor integration process*, whereby the brain selects spatial goals for movement; (2) the *sequencing process*, whereby these goals are sequentially ordered; and (3) the *dynamic process* that codes the desired movement into muscle commands. A fourth, conscious process, (4) the *strategic process*, can improve performance by selecting more effective environmental goals or by selecting more effective sequences of sub-goal attainments.

Data from lesion studies, neural recording and neuroimaging suggest that these processes use largely different brain areas. Concerning sub-cortical mechanisms, which interact with most cortical processes, it has been proposed that the basal ganglia use reinforcement learning to process rewards based on errors in reward prediction; the cerebellum uses supervised learning to develop correlations ('internal models') based on errors in performance, in particular related to timing aspect of motor coordination; while the cerebral cortex uses unsupervised learning to develop topographic representations and predictive coding of sensory signals based on the statistics of the environment.

With the strong development of neuroprotection and methods for neurogenesis in the treatment of nerve injuries, it becomes increasingly clear that the capacity of re-learning of the CNS will become the limiting factor in achieving functional restitution after nerve lesions. More intense research in this area will not only bring new concepts to human neuroscience, but certainly also strengthen the theoretical basis of clinical attitudes in the context of neural diseases and trauma. The outcome may contribute not only to development of new techniques for diagnosis and prognosis of affectations of human behaviour (always effectuated by movements), but also to the development of better routines for evaluations of

clinical treatment and rehabilitation regimes, and to better aids for handicapped individuals. A number of conditions such as stroke, and cerebral palsy require new strategies for rehabilitation to improve function by re-learning, where neuronal networks of healthy brain areas need to be exploited to partly compensate for the functions critically dependent on the injured neural tissues.

Some central research questions are:

• Based on modern concepts of action planning and control, what is the most adequate way of optimizing relearning after neural injury and how does this way relate to type of injury (e.g. lesioned brain area, peripheral neural and mechanical injuries)?

• To which degree will a depiction of regional changes in brain activity or cortical network differences as a function of learning success help us understand why individuals fail to learn, and how one might foster learning and re-learning success both on a cognitive and biological level?

• Research should seek to obtain basic knowledge that will lead to development of novel methods and designs for re-learning protocols tailored to the individual patient for achievement of optimal results. For example, to which degree can the status of the brain function after a lesion (as assessed by functional brain imaging or other techniques) be specifically mapped onto optimum rehabilitation protocols?

3.2 Computational modelling in research on learning processes

3.2.1 Computational models of memory

Memory models are an intermediary step between theories and experiments. They represent embodiments of theories into simulated realities more amenable to study, comparison with real experimental data and prediction of nontrivial consequences of the underlying theory. Constructing scientifically productive models requires both an understanding of the systems and theories to be modelled and modelling skills. Memory models can be compared and judged by many different criteria, including biological realism, ability to predict new phenomena, robustness, simplicity, analysability and evolvability. Quantitative and computational models enable a close link with empirical experiments while allowing theory-driven organisation of the empirical data.

Memory models can be classified depending on how quantitative they are, on the level of abstraction from biology and on the scale of the modelled system. At one extreme lies detailed biochemical and biophysical models of cellular and molecular processes, at the other we find models of semantic networks and distributed representations. In the latter case, the model objects have no clear-cut correspondence to biology and may even be unrelated to psychological representations. They are used mainly to represent salient properties of memory processes. In between one finds connectionist models consisting of simple units and connections, corresponding to neurons or groups of neurons and synapses respectively, modelled using more or less biologically inspired dynamics.

A modelling strategy that has often proven fruitful is to develop a suite of models at different levels of abstraction for the same neuronal system with the aim to transform in a well-defined fashion from biologically fine-grained and detailed to gradually more abstract descriptions. The latter help to pinpoint and elucidate the fundamental mechanisms behind the functioning of a complex system as the

starting point for theoretical analysis and for design of brain-like algorithms and architectures aimed at technical applications.

Along the scale axis, memory models range from studies of synaptic learning processes and small-scale neuronal networks over larger networks to networks of networks, memory systems and in some cases entire simulated agents that may interact with a simulated environment and other agents. Nervous systems typically comprise a very large number of neurons. With present day computers it is feasible to simulate hundreds of thousands of neurons and millions of synapses at a reasonable level of biophysical detail. It is still, however, far beyond the capacity of today's supercomputers to handle a neuronal network model the size of the human brain. A common practice today is therefore to work with *sub-sampled* network models in which the number of neurons is reduced to a small fraction of those actually present in the target system.

Computational memory models emerged historically mainly from early neural network simulations and learning algorithms, although independent formalizations such as the Rescola-Wagner model of conditioning and the symbolic paradigm of classical artificial intelligence (AI) also contributed. One vital strand consists of neural network and connectionist models, taking inputs from cognitive neuroscience on all levels. Another strand consists of convolution models of distributed memory, less involved with biology and more directed towards explaining observations in psychological memory tasks. Statistical models of learning form a third group, mostly linked to the machine learning field, but they are also applied to high-level models of learning and development.

Computational models and simulations are today accepted as very important tools in neuroscience, forming the core of the field of *computational neuroscience*.[3] This methodology has a unique potential to enable understanding of the very complex dynamic and non-linear processes underlying the functioning of biological nervous systems and in the end the human brain. Most parts of the brain have already been modelled with some success. In a biophysically detailed network model of a particular system, its constituent neuron types as well as their synaptic interactions have to be adequately represented. Available data about the system must be collected from literature and experiments and be entered as parameter values.

Associative memories have been the mainstay of more abstract computational models of the brain's memory networks. While strict feed-forward neural networks trained using supervised learning are poor representations of biology, they have contributed by demonstrating how distributed parallel systems are able to learn, create internal representation and to show nontrivial emergence of memory function. Memories with internal feedback and more biologically realistic Hebbian learning rules produce auto-associative processes that can be mapped both to biology and to psychology. Models of working memory have mainly dealt with the issue of how persistent neural activity is maintained in networks with feedback. A large number of models have explored both persistent activity in cortical networks in general and its role in models of prefrontal cortex, in particular during delayed match to sample tasks. The distinction between different memory systems like working memory, short-term, episodic and long-term memory is only beginning to be explored using computational models.

[3] See e.g. Churchland and Sejnowski (1994).

Hippocampal memory models have been developed in order to better understand the function of the medial temporal lobe in the light of the memory consolidation paradigm. While some models strive for low-level descriptions of the functions of the subsystems, many aim at constraining the entire long-term memory system and the consolidation account.

Quantitative conditioning models have a long independent history but have in the 1990's increasingly become models of the neural systems underlying conditioning. They are also related to models of reinforcement learning, emotional memory and memory modulation. The former two are mainly systems level or agent models, while the modulation models mainly seek to understand how parameter changes in cortical memory networks enable shifts in function without any shift in architecture.

Development, childhood learning and language acquisition have been investigated using a variety of models. Many have been simple, nearly qualitative connectionist models that have demonstrated nontrivial effects though they have also been criticized heavily for hidden assumptions. Statistical and dynamical systems models have also been applied, giving alternative accounts. Agent-based models have recently emerged as a hot topic, enabling both greater embodiment and social cognition.

The most successful types of memory models have had an intermediate level of abstraction, allowing them to link to empirical data and underlying biology while still allowing high-level interpretations. They are not overly bound by data, making them less sensitive to lacking or contradictory data, but still realistic enough to produce experimentally testable predictions and inspire variant models.

One of the main white areas on the memory modelling map is self-direction: in order to model increasingly nontrivial memory tasks more autonomous systems are needed in which the memory is a core component in the perception-decision-action cycle. This ties in with agent-based modelling and social cognition; another area where much work remains to be done and significant results are likely with relatively simple models.

Multi-level and hybrid models including both abstracted systems and biologically inspired modules are another promising approach. By using a modular approach where well-understood subsystems are used as part of high-level systems more complex memory phenomena can be modelled. Emotional memory and consolidation are likely targets for such systems.

The enormous growth in data availability and computing power suggests the need for new ways of organising and maintaining extensive simulations. Closer links between modelling and clinical brain research is likely to prove fruitful. In the longer term applied quantitative and computational branches of memory psychology and cognitive neuroscience are likely to enable a number of applications in education, psychology, medicine and computer science.

Some central research questions are (also see Anders Sandberg's report, Attachment 3, for further discussion of these):

• What is the most adequate way of quantitatively describing the dynamics of the brain's memory networks in memory encoding and recall? What is the interplay between attention, working memory and long-term memory?

• How can knowledge about the dynamics and modulation of synaptic plasticity and neuronal properties embodied in computational models be related to phenomenological learning processes?

• How can we use computational models of neuronal and synaptic learning processes in e.g. the design of computer based technology for learning, diagnosis and therapy of attention and memory disorders and deficits in the young and the elderly?

• What more is required to create abstract computational models of brain function that can be taken advantage of in the development of brain-inspired information processing technology, with applications e.g. in man-machine interaction?

3.2.2 Learning in intelligent agents and technologies

Another area where computational modelling is central is in the construction of artificial agents such as robots. In general, an autonomous and intelligent agent can be described as a hardware or (more usually) software-based computer system that enjoys the following properties:[4]

- Autonomy: agents operate without the direct intervention of humans or others, and have some kind of control over their actions and internal state;
- Social ability: agents interact with other agents (and possibly humans) via some kind of agent-communication language;
- Reactivity: agents perceive their environment, (which may be the physical world, a user via a graphical user interface, a collection of other agents, the Internet, or perhaps all of these combined), and respond in a timely fashion to changes that occur in it;
- Pro-activeness: agents do not simply act in response to their environment, they are able to exhibit goal-directed behaviour by taking the initiative.

Some examples of current autonomous designs include the robot dog Aibo and the walking humanoid Qrio, both designed and manufactured by Sony, Husqvarna's autonomous lawn mower, the autonomous vacuum cleaner Trilobite by Electrolux, and NASA's Mars Rover designed for planet exploration. None of these systems fulfil all of the above characteristics in their full extent. For instance, more advanced operations, if at all possible, still require human remote control.

There could, however, be many applications of more advanced autonomous agents, robots and smart devices in industry, farming, and forestry as well as in the health care and service sectors and in the household. Such machines could relieve humankind from dangerous, heavy, or otherwise undesirable work and they could also exist for amusement and company. Much research is today devoted to the issue of how to achieve more powerful intelligence including learning capabilities, to provide more flexibility and the ability to learn to operate efficiently and without human guidance in an environment partly unknown to the designer.

In a general sense, living creatures can be considered prototypical autonomous learning systems. There are tasks that animals, including humans, do with apparent ease but that no robot or agent is yet capable of. One obvious human example is intelligent reasoning and thinking and the ability to learn and to solve unstructured or poorly structured problems without explicit rules. Capabilities we

[4] See Wooldridge and Jennings (1995), p. 2.

share with some other animals include highly accurate recognition of complex objects such as faces and a high degree of mobility.

The field of machine learning has traditionally not paid much attention to the mechanisms underlying biological information processing and control. Today this is changing somewhat, partly due to the dramatically increased knowledge about the brain. Research on artificial neural networks and systems as well as the connectionist approach in cognitive science are representative of this trend. For the further development of such brain-inspired technologies, progress in understanding of brain function including learning processes will be of great significance. Abstracted and scaled-up versions of biologically detailed models of the neuronal networks of the brain, as developed in the area of computational neuroscience, may be used as the starting point for design of "artificial nervous systems" in robots and virtual agents.

In connection with research on autonomous intelligent agents it would be relevant to develop demonstrator applications, selected to be highly relevant for a programme on learning processes. One could, for instance, consider developing trainable man-computer interfaces and computer applications for educational, diagnostic and/or therapeutic use.

There are already some attempts to design interactive and adaptive software agents that are able to diagnose the learning profile and level of proficiency of the learner and to present tasks in a manner that optimises learning rate and persistence of learning effect. Another similar application concerns further development of computer game type applications, which has already proven beneficial in the treatment of ADHD (Tegnér and Klingberg, see below).

A sample of research questions in the intersection between research on learning processes and autonomous and intelligent learning agents are:

• How can the multiplicity of memory systems (episodic, working, long-term, declarative, semantic, procedural etc.) be understood and used in the relation to the design of learning artefacts?

• Is there a need for a mechanism corresponding to emotional modulation of biological memory in artificial learning agents and what is its nature and role?

• Can memory be transferred in a more intact form between "generations" of artefacts and what would be the benefits and drawbacks of this possibility?

• Can the design and study of artificial brain-inspired learning and acting systems tell us something about the nature of and interaction between the corresponding biological functions?

3.3 The learning individual

3.3.1 Concept formation

Concept formation is a fundamental aspect of human learning, since it involves the very *structure* and *contents* of what we are learning – the concepts. If you have misunderstood the basic concepts of a particular knowledge area, it does not matter how many facts you learn, since your knowledge will be flawed.

A revealing example of such a conceptual confusion comes from Vosniadou's (1994) studies of how children understand the concept of the earth. Even though children are exposed to spherical models of the earth in various ways, they have considerable difficulty in understanding the concept of the earth as a rotating sphere whose revolutions around its axis cause the day/night cycle. They

categorize the earth as a physical object and apply to it the presuppositions of everyday physics, e.g. that it is flat and that is governed by the up/down direction for gravity. When they combine this with the information that the earth is a sphere, they end up constructing various more or less incorrect models. Before children have a clear grasp of the concept of gravity, they will not form the correct model of the earth.

Results like this show that it is not sufficient that schools and other educational systems present the students with the correct concepts, but one must also make certain that elements from a more naïve theory, such as "folk physics" or "folk biology" do not remain as parts of their understanding of the concepts. As was argued in section 3.1, this kind of unlearning is in general very difficult to achieve.

There are many theories of concept formation within various disciplines such as philosophy, cognitive psychology, developmental psychology, computer science (machine learning, connectionism), and to some extent also linguistics (semantics) and neuroscience. Thus the area is truly interdisciplinary, but the various theories differ widely in their assumptions concerning the structure of concepts and in their modelling of how they are learned. As in most other areas of learning, researchers from different disciplines often speak past one another. Concept learning is a prime area where interdisciplinary research could remedy the situation.

There are many open research questions, the answers to which will have a deep impact on the way different kinds of education should be organised, on how to bring up children and on how to provide the best environment for different forms of handicap. The following is a list of the most pressing research topics:

• Philosophical and traditional computational theories often claim that concepts can be defined with the aid of *rules*, while other theories in psychology and connectionism argue that concepts are based on *similarity* (focused around prototypes). This fundamental division is still hotly debated by the researchers in the area. The psychological experiments that have been conducted to settle the issue are in general based on a narrow and rather artificial concept learning setting. Much more knowledge is needed about how people actually learn and construct concepts in real life situations.

• A third alternative view is that a concept is a kind of mini-theory (Gopnik and Meltzoff 1997). This so-called theory-theory presumes that even small babies have theories. What would it mean and how could we find out?

• Research on how concepts are handled in the brain is still in its infancy (Pulvermüller 2001). We need substantial research to find out what constraints neuroscience puts on theories of concept formation.

• Children learn to understand about 10 new words per day. Even though there is not a unique mapping between words and concept, this entails that human concept learning is extremely fast, in that each concept is determined from a single or a couple of encounters. However, most computational models of concept learning, in particular within connectionist modelling, require extensive training with a large number of instances. Here, however, new interesting developments regarding fast acting learning rules (synaptic plasticity) may open up for a better understanding of mechanisms behind short-term and working memory. What kind of computational models may more accurately describe the rapid human learning?

• Education often involves negotiations of partially understood concepts. We need to know how this negotiation functions. A related question is: how do group processes of concept learning function?

• Children are building knowledge all the time in their everyday activities inside and outside formal institutions. How does it work? How much does education influence the constructions? What is the relationship between learning in daily practices and learning in institutional settings?

• How much does language influence concept formation (in childhood as well as in adults)?

• How does intersubjectivity of meaning come to be established in learning situations? The ability to achieve shared reference (joint attention) is a necessary element in this process and central to all human learning (Tomasello 1999).

• Recent theories of language learning emphasise that children exploit the fact that speakers have *intentions* to communicate when they speak (Bloom 2000). Thus language learning and concept formation depend on children achieving intersubjectivity and having a so-called "theory of mind", i.e. that they understand the emotions, intentions and beliefs of others. However, the methods for determining children's theories of mind are yet underspecified. How can we make them more operational?

3.3.2 Education

Education is a very complex social phenomenon that exists in many forms: all the way from preschool up to adult and university training. One must also be aware of the fact that schools have a range of responsibilities that go beyond a narrow conception of learning. They have broad socialising responsibilities of promoting attitudes, skills, and knowledge that are vital for the democratic society. The average citizen now goes to school 12 or more years, and learning is very differently organised during this period. Furthermore, one must give recognition to the fact that the actual practices of education are very diverse, to put it mildly. Schools and teachers differ as to how they organise classroom practices. Education is fundamentally an ideological activity, and as such it has to be informed by a broad range of considerations where research on learning is but one aspect.

One element of schooling that we consider relevant for a research programme concerns the role of computers and digital media. Computers are quickly becoming natural components in many educational settings. Some years ago, there was a tendency to believe that if we only could install enough computers in the school, many educational problems would be solved. However, students as well as teachers are to an increasing extent questioning the value of information technology in education. Even if computers are frequently used for word processing, information search, e-mail and chatting, the worry is whether these tools really improve how students learn.

The fundamental problem seems to be that we do not know enough about the interplay between learning and tools for learning. One reason for this may be that researchers in pedagogy have been focusing on *descriptions* of what goes on in schools and other educational environments and have hardly been interested in constructive suggestions for how education ought to be conducted. Eklund (1995, 2000) has surveyed Swedish Ph.D. theses in pedagogy during the years 1988-1997. He has found that only about 10% of the theses deal with methodological problems concerning education, while the remaining 90% can be classified as studies of the conditions of education.

In contrast to this, the OECD report *Understanding the brain* claims that "the emerging findings of cognitive neuroscience call into question some of the fundamental building blocks of traditional education – schools, classrooms, teachers (as we understand the profession today), or even the curriculum, and even concepts like intelligence or ability" (p. 11). Apart from taking the results from cognitive neuroscience into account, the potential of modern information and communication technology seems far from fully exploited in education. We clearly need more developed and more encompassing theories of learning that can account for these potentials.

One may ask why there is no general theory of learning that can be applied to the problems of education. For comparison, in physics and in medicine theoretical gains have led to immensely powerful practical applications. Why has psychology and the brain sciences not had the same effect on education?

An analogy with the development of medicine may be helpful here.[5] Before modern medicine was developed there was a large body of folk medicine – practices to treat illnesses that were based on a mixture of traditional knowledge of the effects of various herbs and treatments with myths and superstition. These practices did not have any backing in the form of controlled experimental testing. They often resulted in conflicting recommendations and, in retrospect many of them were directly harmful. Gradually, this epistemologically chaotic state has been replaced by modern medicine that is based on increased knowledge about the functioning of various bodily systems together with strictly controlled experimentation when new drugs are introduced. We are now reaching the state where new drugs can be chemically designed rather than found by laborious trial-and-error testing on laboratory animals.

The analogy we want to hold out is that our knowledge of how education should be practised is to a large extent still on the level of folk medicine. Most instructional practices are motivated by a combination of folk psychology and a reference to tradition. This does not in itself entail that the educational practices are bad, only that in most areas their scientific grounding is shallow.

The analogy with medicine could be carried further in the sense that the level of clinical research, i.e. co-operation between scholars and teachers/students, has not been developed. The considerable sums of money that are spent on education are not coupled with systematic attempts to create a bridge between research and the school. If we extend the comparison with medicine, an overwhelming majority of the professors are in clinical areas and have a specific responsibility for attending to the links between basic research and theoretical progress. Such a system is completely lacking in the educational sector. Recently, the Committee for Educational Science of the Swedish Research Council has taken an initiative to build up a programme on 'praxis-related research' that is intended to provide models for such co-operative enterprises. To further this ambition it will be necessary to involve the community level since it is here that the resources for education are controlled and it is here that the responsibilities for developing education lie.

The reason why folk psychology still functions as a foundation is that the sciences of learning are not as mature as one could hope. As should be clear from this report, what one finds is not one unified theory of learning, but a multitude of theories on different levels of explanation – from learning in neurons to learning

[5] See the OECD report *Understanding the Brain*, p. 35 for a similar analogy.

in organisations. In most cases it is difficult to see how the theories can be made to work together for more general explanations and recommendations. We see this as a strong argument for intensified basic research on learning processes that in the long run can generate more unified underpinnings for different educational practices.

To be sure, there have been attempts at such unification. For example, Skinner (1965) presented a theory of instruction based on the behaviourist theory of learning. However, later developments have found the behaviourist ambitions to create a general theory ill informed and mistaken.

The main theories of learning in educational settings can be grouped under the following headings:

• *Classical cognitivism,* which sees the working of the brain as information processing ("the brain as a computer").

• *Behaviourism*, focussing on stimulus-response connections, where modern versions of it refer to connectionism and neuroscience.

• *Constructivism*, a central tenet of which is that we construct our own knowledge.

• *Socio-cultural theories* that claim that cognition and learning cannot be understood independently of the social and cultural context in which theses processes occur.

• *Situated (and embodied) cognition*, where it is claimed that cognition does not only take place in the brain, but cannot be analyzed in isolation from the environment (including the body). Situated cognition has a close affinity with socio-cultural theories.

In spite of the fragmented nature of the sciences of learning, we believe that nevertheless there is much to gain from the different theories that have been formulated and to develop these further given constraints from the experience that has been collected in different educational settings. The strategy should therefore not be to search for Utopia, but to be more eclectic: take what is available today and use it as a basis for recommendation on instructional practices, in particular practices involving ICT.

One theme that has come into the focus of educational research during the last years, but which runs through the theories above (except for behaviourism) is *metacognition*, or the ability to reflect on one's own thinking. In the present context, the role of *metalearning*, i.e. to learn about learning, is particularly important. Several empirical studies show that finding educational tools that improve students' meta-learning also have clear positive effects on their learning.

Metacognitive knowledge about problems helps the learner to determine what is known, what is unknown and what is being asked in the problem situation. Metacognitive knowledge about procedures guides the learner on how the information is encoded. It also involves planning and selecting a sequence of steps to solve the problems (Davidson and Sternberg 1998). Children who are aware of why, when and how strategies should be used are more likely to be able to use those strategies successfully (Pressley, 1984).

However, the mechanisms that connect meta-learning with learning are to a large extent unknown. Here lies a research field that, once seriously dug into, could reveal many treasures for educational scientists. The relevant research does probably not fall within the traditional disciplinary borders, but should be joint efforts by neuroscientists, cognitive scientists and educationalists.

Another theme that is related to meta-cognition is the role of *understanding* in learning. Learning a given set of facts is one thing, learning abstract theories is another, but learning to understand how the theories make sense of the facts should be the obvious goal of learning. Nevertheless, the very concept of understanding has been step-motherly treated in research. To be sure, the tradition of hermeneutics puts "Verstehen" in the centre, but here the objects of study are in the first hand literary works or objects of art. When it comes to studying, for example, the role of more mundane "aha"-insights in ordinary students and the role of these insights in the learning processes, research is still in a virginal state. And a focal theme for educational science should be to compare educational practices that foster understanding to those that do not. Again, relevant research does not fall within the traditional disciplinary borders, but require new kinds of initiatives.

A third theme is that individual learners show considerable *cognitive variations*. For example, some people think primarily in spatial structures, others in verbal format, and still others prefer to represent information as socially organised. One domain that addresses this issue is research on *learning styles* (Sternberg, 1997). It has been shown that there is a correlation between gender and learning style. However, as is common in such studies, the variation within the sexes is much larger than the overall difference between them.

This theme is particularly important when it comes to the design of educational media. Traditionally, schools books have been written with the assumption that "one size fits all" (Gulz 1999). However, one of the great potentials of ICT is that it is nowadays feasible to design different variants of an educational material that are adapted to different learning styles. To achieve this, close cooperation between educationalists, cognitive scientists and programmers is required.

Other issues that have come to the fore in recent decades are the challenges and possibilities of media development, demographic changes and sensitivity to culture, ethnic and gender differences in learning processes and learning activities. Such features are mostly ignored in research on learning and cognition. This is no longer feasible, since there is a growing recognition of the centrality of such dimensions for the establishment of successful learning practices.

Some key research questions are:

• What is the relationship between developing higher lever thinking skills and emerging domain-specific cognitive structures?

• How does metacognition influence affective aspects of learning? How do metacognitive processes develop in relation to cognitive ones, and vice versa?

•What is the role of metacognition in the development of conceptual knowledge in different domains? How do metacognitive processes develop with age?

• What is understanding and what is its role in learning? How can it be promoted?

• What are the implications of media changes for the organisation of learning practices in schools?

3.3.3 ICT and learning

Information and communication technology (ICT) is seen as having a great potential for revolutionizing education. Large investments in term of computers and political commitments have been made. Teachers are assumed to rapidly make use of ICT at schools and universities, both in the classroom and as a tool for

distance education. However, the general trend is that ICT is added to an existing educational system, and then it is expected that students will immediately show improvements in terms of their motivation for learning and their learning achievements.

Furthermore, digital technologies are currently transforming work practices in many, if not most, settings. Traditional industrial production is modified from manual labour into work that implies surveillance, monitoring, and coordination. The pace of this transformation has considerable consequences for education and for learning in the work place. The dynamics of this development also affect the relationship between learning practices inside and outside schools. Institutional forms of learning have to focus on general and generative types of knowledge and this is a challenge when attempting to avoid too abstract modes of teaching and learning.

Since ICT tools have only recently been introduced in educational practices, one cannot hope that these practices will tell us what the optimal use of ICT in education is. Ideally, we should be able to derive what is the best use of these tools from the available theories. However, the fragmentation of the theoretical field makes it very difficult to formulate any generally applicable recommendations at the level of implementation.

It is not the number of computers in the classrooms that is the bottleneck for the success of ICT in education, but rather our lack of understanding of the cognitive, emotional and motivational processes underlying human learning. What is missing in much of the current debate is a theoretical perspective on the learning process that can be used as a foundation for creative recommendations of how to construct pedagogically valuable tools based on ICT. Such a perspective will also result in grounded recommendations on how learning processes, with or without the support of ICT, should be evaluated. In particular, theories concerning how learning can be mediated by ICT ought to build upon what is known about human cognitive processes. In the case of so-called e-learning, Maria Larsson's report (Attachment 4) bears witness of how cognitive science can be of help in the design of ICT systems.

Expressed in general terms, the development of computers and digital technologies during recent decades represents a challenge to education and research in education on at least two different levels. One of the critical issues concerns the manner in which computers and other features of information technologies can be incorporated into education and contribute to improving processes of teaching and learning. Since the early 1960's, in fact well before the introduction of the desktop computer, there had been systematic attempts to explore how computers can be utilised to promote and facilitate learning in schools and in other settings. This work developed from a rather simplistic, behaviourist notion of how computer-assisted instruction (CAI) would replace the need for teacher-student interaction, and traditional teaching and learning activities, via attempts to design intelligent tutoring systems, to present day work on issues of computer supported collaborative learning (CSCL).[6] In the latter tradition the focus is not on attempting to replace the teacher, but rather the aim is to design contexts for learning in which technology facilitates and supports the activities that learners (and teachers) engage in.

[6] Koschmann (1996).

Research on these issues of how technologies can support human learning is very intense at present, and nowadays one finds a number of different fields of research that have become specialities in their own right.[7] These would include areas such as distance learning, human-computer interaction, multimedia research, on-line learning communities, and the uses of simulations and other representational technologies in educational settings and in various academic subjects. In addition, research in areas that deal with the compensatory potentials of digital technologies for people with special needs is intense. Within these fields there is also much work going on at the intersection between research and development, what could be referred to as instructional design research.

On another level computers and digital technologies represent a challenge to education, and to our conceptions of knowledge and learning, in a very profound sense. These resources currently transform many features of society including our work practices, our leisure activities, the media that surround us, and the manners in which we consume goods and cultural experiences, to take just a few examples. Also, through digital technology the amount of information that is accessible for people has grown dramatically. As a consequence of these changes, our modes of learning and communicating are transformed at the individual as well as the collective level. New skills are required from individuals who are operating in new work environments. Digital literacy and numeracy, i.e. the manners in which we are able to navigate in cyberspace and make use of databases and a range of on-line resources, are more complex than traditional skills in these areas. For instance, they require language skills and abilities to locate and critically evaluate information in terms of its relevance and reliability.

Also at the organisational level, work patterns modes of communication, and learning are changing as an effect of the possibilities of the new technologies to allow for co-operation across time and space. The traditional industrial production is gradually being replaced by 'knowledge work' in which people monitor and steer production through technological tools. This is a rather dramatic shift in which new kinds of competencies are required. Furthermore, technologies are modified so often nowadays that continuous learning is necessary in many professions and work contexts.

Some research questions:

• How can visualisation and simulation with ICT tools increase understanding and improve education in general?

• How can ICT-based educational programs be designed so that they take individual learning styles into account in an optimal way?

• What is the nature of learning that is supported by ICT when used in formal education?

• How can computers and ICT resources be further used to stimulate the development of compensatory learning practices for people with specific or general learning difficulties?

• What are the gender effects of using ICT in schools and other contexts of learning?

• How do ICT and ensuing changes in media use affect communicative practices in formal education?

[7] For representative work, see Bliss, Säljö, and Light (1999); Jonassen (2000); Wasson, Ludvigsen, and Hoppe (2003).

• How are the kernels of knowledge and skills of various professions transformed by the introduction of information technology in production? What does this imply for learning?

• The promotion of functional skills in the areas of digital literacy and numeracy are important areas of research. What are the critical differences between traditional literacy skills and those made necessary by the new technology?

3.3.4 Playing and learning

There is a large body of research on play and learning in preschools and schools. Play methodologies can strengthen motivation, engagement and sense of emotional security in a learning situation. Many researchers point out the shift in understanding play from recreation to pleasurable learning. Other play discourses – psychological abreaction, cultural expression, fiction – become overshadowed by the discourse of play as learning and development. For this reason, it is motivated to distinguish between "play" (as a biological function, a self-motivated activity, and a form of cultural expression) and "playful learning" (play-like learning activities initiated for specific learning purposes).

The roles of the body, movement and physical activity have traditionally been less valued than cognitive abilities in the educational system, a fact that still permeates the design of both school system and premises. Recent research in neuroscience and other disciplines offers new perspectives on the relationship between motor behaviour, cognition and play.

- Studies on animals show that the scheduling of specific play behaviours matches sensitive periods in the development of the central nervous system (performance-dependent development).
- New knowledge of the mirror neuron system points to the amount of neural resources dedicated to understanding others' physical actions, and as a consequence, to the importance of imitation for learning.

This offers new perspectives both on the possibility to model activities for specific learning or rehabilitation purposes, and to the rationale of "autotelic" play activities. This field has potential to show significant progress during the coming years. It has important implications for issues of both learning and health. The culture of physical inactivity is still present in the design of school and school premises, and future forms of educations such as e-learning remain in most cases in the same paradigm.

Technology changes children's lives and also the conditions for education. Many children are extensive media users from an early age. Media offers virtual play spaces and many occasions for informal learning. The skills used for playing computer games or chatting are in many cases also valuable in a school context

Within the disciplines of Human-Computer Interaction and Ubiquitous Computing an important research issue deals with the design of computer-based learning environments and artefacts for playful learning. "Smart toys" help children explore complex mathematical formulas in a hands-on manner. Computer-augmented environments can be designed to support movement and interaction between people and computer systems simultaneously. These design initiatives are still in their beginning, but important to pursue further – especially in view of the amount of time future learners are expected to spend interacting with computers.

Most play theories and play research deal with children, which give them a limited potential when it comes to adults. Play theorists as Huizinga, Apter and Czíkszentmihályi have developed theories that also cover adults' play. These have been used successfully to understand the motivation and behaviours of adventure tourists. Also within participatory design, play is used to model collaborative design activities. There is reason to believe that many cultural, social and learning activities of "non-children" could be better understood and designed for using play theory.

Some research questions:

• Why is play motivating? The strong motivational factor in play is widely recognized, but wherein lies the motivation? How does motivation relate to the content of play, the form or the social context? Does the motivational factor change depending on the age of the players?

• Which are the informal learning processes involved in children's play and use of media? How do oral culture, mass-media content, peer pressure, motivation, and self-image contribute to children's informal learning in play and trough the media? What is the rationale of children's preferences in informal learning? The gender aspects of such socialising processes are also important to analyse.

• How and why do adults play? The research on play focuses almost exclusively on children and play. Adults play too – in sports, in gambling, with their mates, through daydreaming, through participation in festivals and in many other forms. Huizinga and others point to the importance of communities in play – and that the play communities often have influence far beyond the play situation. Ethnographic research on adult play could contribute to understanding of and design for learning and leisure activities for grown-ups.

• How can play add to life quality for aged people? Czíkszentmihályi describes how "flow" helps maintaining a sense of meaning in old age – whether expressed as artistic practice, scientific endeavours or golf playing. Neuroscience points to the importance of regular use of mental and motor systems in order to maintain their level of performance. How can play – games for rehabilitation or training, or social leisure activities, add to life quality of old people?

• How can computer technology be used to design pleasurable learning environments that allow for movement? Computers, smart toys and digitally augmented environments open up new possibilities to shape playful learning processes. Learning and computers was initially envisioned as one person sitting in front of one computer. Today existing technologies allow us to interweave computers and physical environments, and to devise forms of interactions that allow for movement and physical activity.

3.4 Learning organisations

It is a truism that learning does not only take place at schools or in universities, but it is a life-long process that involves learning in working places as well as in everyday life. Recently more research interest is being devoted to learning processes that occur outside the traditional educational institutions. In particular, the rapid transformation and technologisation of various kinds of working places motivate a sharper focus of learning in organisations.

The fields of learning organisations and learning in organisations are extremely heterogeneous and it would be impossible to give a representative survey in this document. Furthermore, there seem to be many aspects of what goes under the

name of learning in organisations, many of which are not relevant for our purposes. Here, we will focus on how theories of organisational learning can possibly relate to the other research areas that have been presented. One central question is to what extent there are aspects of learning processes that are only found in organisational or group learning and that have no counterpart in individual learning.

One very influential theory of organisational learning is the one presented in Senge's (1990) book *The Fifth Discipline*.[8] The five disciplines are: systems thinking, personal mastery, mental models, shared vision and team learning. Systems thinking means using system dynamics as a modelling tool for understanding the development of an organisation. Personal mastery involves continually developing one's personal vision. Mental models are a set of tools that can be used to solve problems in the organisation, individually or collectively. Having a shared vision means that everybody in the organisation agrees that a certain picture of the future is guiding the activities of the organisation. Team learning involves mastering the practices of dialogue and discussion, but also recognizing patterns of interaction that undermine learning.

If one sees these five "disciplines" from the point of view of learning processes, the three first ones basically concern individual learning. Furthermore, "shared vision" does not really concern learning but rather motivational aspects of the organisation. This leaves us with "team learning" as the only part directly relevant to organisational learning. In Senge's theory the emphasis of team learning is on the role of *dialogue*. As we shall see, this factor is central for learning in organisations.

Another much discussed theory of organisational learning is the "double loop theory" proposed by Argyris (1992). In general, learning involves the detection and correction of error. Single-loop learning takes place when goals, frameworks and strategies are taken for granted. Where something goes wrong, the individual or the organisation looks for another strategy that will address the problem and work within the given framework. In other words, goals, plans and rules are operationalised rather than questioned. Double-loop learning, in contrast, involves questioning the role of the framing and learning systems that underlie actual goals and strategies. The alternative response is to question the governing variables themselves, to subject them to critical scrutiny. This Argyris describes as double-loop learning. Such learning may then lead to an alteration in the governing variables and, thus, a shift in how strategies and consequences are framed.

When the error detected and corrected permits the organization to carry on its present policies or achieve its presents objectives, then that error-and-correction process is single-loop learning. This involves following routines and some sort of preset plan – and is both less risky for the individual and the organization, and affords greater control. Double-loop learning occurs when error is detected and corrected in ways that involve the modification of an organization's underlying norms, policies and objectives. This is more creative and reflexive, and involves meta-cognition, i.e. the possibility to reflect on one's own methods and processes.

Again, the double loop theory is so general that it can be applied to individual as well as organisational learning. An important question in the current context is therefore what aspects make double loop learning different in an organisation

[8] A condensed summary can be found at http://www.rtis.com/nat/user/jfullerton/review/learning.htm.

compared to processes of an individual that learns. Here it also seems that dialogues and negotiations play an important role.

If we for the moment leave what is traditionally called organisational learning, Vygotsky's socio-cultural approach to learning also brings dialogues into focus. According to this approach, learning is constituted by the appropriation of the social processes and communicative acts we share with other individuals. The most well known theoretical contribution of Vygotsky is probably the "zone of proximal development." The idea is basically that in collaboration with other students and the teacher, the student can reach further in understanding and problem solving than could be achieved on her own. The teacher functions as a form of scaffolding, supporting the students to solve tasks that are above their current level of understanding, and thus guiding the students through their individual zone of proximal development.

Another expanding field, inspired by socio-cultural research, concerns the study of literacy practices and literacy learning in organisational contexts and at the work place. This interest has grown out of the increasing demands for literacy skills in modern 'fast capitalist production systems' (Gee, Hull, & Lankshear, 1996), which rely heavily on texts and documentation through computer technology. When texts and computer technologies infiltrate most production systems, work practices become more abstract and demanding. This is an area that is well worth exploring from an organisational as well as an individual perspective.

The theories we have used to exemplify organisational and group learning, as well as many other in the same field, have in common that they emphasise dialogues as necessary for learning in groups. Unfortunately, these theories do not explain very clearly what are the mechanisms of learning in dialogues.

In Senge's theory, team learning involves mastering the practices of dialogue and discussion, the two distinct ways that teams converse. In dialogue, there is the free and creative exploration of complex and subtle issues, a deep "listening" to one another and suspending of one's own views. By contrast, in discussion different views are presented and defended and there is a search for the best view to support decisions that must be made at this time. In socio-cultural theories, interaction and dialogues are seen as foundational for the production and reproduction of knowledge and skills in any activity.

Bohm (1996) has proposed the following necessary conditions for dialogues:

- All participants must "suspend" their assumptions, literally to hold them "as suspended before us";
- All participants must regard one another as colleagues;
- There must be a "facilitator" who "holds the context" of dialogue.

The upshot of this presentation of some of the themes within organisational learning is that there is much in this area that is not directly relevant to group learning processes or that can be reduced to the individual learning level. The common factor of what is unique for group and organisational learning seems to be the role of dialogue.

Two research questions can be formulated in relation to these aspects of organisational learning:

• Most writers seem to take it for granted that we know why dialogues are beneficial for learning. As a matter of fact, the learning processes that take place

during dialogue and discussion have been very little investigated, notwithstanding the examples above. This should obviously be a central topic for a research programme on learning processes. Research on learning in dialogues should also be connected to results from psychology, linguistics (pragmatics), cognitive science and, to some extent, neuroscience.

• Another aspect of group learning is that even though most of what is actually learnt might be explained by individual learning processes, the group may strongly contribute to the *motivation* for learning, and hence enhance the process. In other words, the incentive for an individual to learn becomes much stronger if it is shared and reinforced by other members of the group. Senge's emphasis on the shared vision of an organisation is an example of this. Again the role of group motivation for learning, individual or collective, is an area that is in acute need of more research.[9]

4. Potential for an interdisciplinary research programme on learning

4.1 The call for project proposals

In the fall of 2002, we sent out a call for proposals to a large number of Swedish researchers and research groups that we had identified as being, in one way or another, involved in research on learning processes. We got a very positive response and were pleased to receive more than sixty brief proposals for future projects, most of which involve interdisciplinary research. These proposals form attachment 7 to this report. Among the respondents one finds many of the strongest Swedish groups in the area of learning. However, there are some of the more important actors that did not respond so our material does not cover the full potential of Swedish research in the area.

On the basis of the project sketches we organised a workshop November 19-20, 2003, where everybody who had sent in a proposal were invited (around 30 persons attended). We selected eleven projects, ranging from neuroscience to education, which were representative of the fields covered by the proposals. During the workshop the researchers behind these proposals presented their ideas. As a result, very fruitful discussions on the future of research on learning processes emerged.

The large number of proposals and the constructive and optimistic discussions at the workshop give clear indications that there is a very good potential for research on learning processes in Sweden.

4.2 Promising research themes in the proposals

The total set of proposals span a wide area of research topics related to learning processes. In this section we will try to identify some of the dominant areas. Together with the more theoretical considerations in sections 2 and 3, this survey will form the basis for our recommendations in the final section.

4.2.1 Emotion, motivation and learning

In section 3.1 and in the report by Andreas Olsson (Attachment 2), the area of emotion, motivation and learning is identified as one of the most promising areas for future research. In Sweden there is also a good environment for this area. This also is witnessed by the number of promising proposals that we have received:

Arne Öhman and his group at the Department of Clinical Neuroscience, Karolinska Institutet are internationally leading in this area and they have strong

[9] See Hall (2003).

international collaborators. Their proposal concerns the role of conscious awareness in emotional learning. This area connects neuroscience with cognition and it has far-reaching potential applications for all kinds of learning.

Also Jeanette Hellgren Kotaleski's proposal concerning biochemical modelling of reinforcement learning in the basal ganglia fits in well here. Although her work is clearly basic research, through the role of dopamine it may have fairly direct application in work on learnings mechanisms, motor disorders, drug addiction and attentional disturbances.

From an educational perspective, Mats Lindahl, Frank Lindblad and Bo von Scheele propose a project concerning how young people cope with stress in school situations. This is an example of a project where collaboration with neuroscientists could prove fruitful.

There are other groups in Sweden that do highly qualified research on emotion, motivation and learning, for example Christian Balkenius and his associates at Lund University and Anders Lansner's group at KTH (to which Hellgren Kotaleski belongs). Also the proposal by Ingmar Rosén, Magnus Lindgren and Mikael Johansson, presented below, fits in here. Given the research programme we advocate together with a network of Swedish scientists, bridging neuroscience, psychology and education, this research area clearly has a strong position in Sweden.

4.2.2 Memory functions and their consequences for educational and other practices

Learning and memory are more or less two sides of the same coin. As identified in sections 3.1 and 3.2, there are several central research questions concerning the relations between learning and memory. Again, there is internationally first-rate research going on in Sweden on memory functions and their consequences for educational practices as is witnessed by the large number of project proposals that we have received in this area. Here it is impossible to give an overview of all of them, but we just briefly present some of the proposals.

Jesper Tegnér and Torkel Klingberg have already initiated an interesting research project on the possibility of training the working memory of children with attention deficits (ADHD) using specially designed computer games and they have achieved positive results. This is an application of their studies and modelling of the plasticity of the working memory system. The potential for further applications for educational practices is great. These models are also relevant for the development of the memory functions in cognitive robotics and autonomous agents.

Also Karl Magnus Petersson and Martin Ingvar present a broad project on the systems neurophysiology of learning focusing on the adaptivity of the brain. Petersson has studied neurological differences in the brains of literate vs. illiterate subjects. In brief, he has shown that certain areas of the corpus callosum are less myelinated in illiterate subjects. Obviously, along with the previous project, this foundational research may have wide consequences for our understanding of how education affects the brain.

Ingmar Rosén, Magnus Lindgren and Mikael Johansson propose a project where neuroscientific evidence (from ERP, fMRI and PET) is compared to data on retrieval and familiarity of episodic memories. In ERP the error related negativity component (ERN) is correlated to motivational factors.

Timo Mäntylä has proposed a project concerning learning processes and individual differences in executive functions. The main objective is to study the connections between executive functions and memory processes, such as the involvement of executive functions in episodic memory and in meta-memory.

Lars-Göran Nilsson's longitudinal study of the memory functions of 4000 individual Swedes (the Betula project) is an internationally unique project in many respects. The results from this project will have repercussions for research on memory and ageing, but also for various memory dysfunctions. The rather broad programme proposed by Lars Bäckman and Lars Nyberg also ties in well with Nilsson's research and has further implications for cognitive rehabilitation.

Apart from these projects also the proposals by Erik Fransén, Yuri Zilberther and Per Roland, Sverker Sikström, Gunnar Sjödin and the SICS group, Hans Forssberg and Hugo Lagercrantz fall under the topic of "memory functions and their consequences for educational practices." In total, the high number of proposals, together with the considerations in section 3.1, strongly motivates this topic as a central one in our proposal.

4.2.3 Computational models of neuronal mechanisms of learning and memory

As has been argued in section 3.2 and in the report by Anders Sandberg (Attachment 3), computational models of neuronal mechanisms of learning and memory form a fundamental research area that is necessary for the development of theories learning processes and memory with the aim to connect microscopic and macroscopic/behavioural levels. The modelling should build on a synthetic and holistic approach to brain function during different forms of learning and operation. The perspective would range from neurons and synapses to large scale network processes underlying plasticity and learning. This area constitutes a meeting point for experimentalists, modellers and practitioners. The systems oriented perspective also suits the connection to brain-inspired algorithms and architectures for autonomous learning robots and virtual agents.

Several of the proposals presented in the previous two subsections are also relevant for this area. These include those by Sverker Sikström, Jesper Tegnér and Torkel Klingberg, Christian Balkenius with associates, Anders Lansner's group including Erik Fransén and Jeanette Hellgren-Kotaleski. The groups of Yuri Zilberter and Per Roland, Hans Forssberg and Hugo Lagercrantz, Karl-Magnus Petersson and Martin Ingvar, provides important experimental connections for the more theoretically oriented efforts. The proposal by Jussi Karlgren and Magnus Sahlgren also falls under the heading of this subsection. It is about building and evaluating models of language acquisition. Language acquisition is, of course, a central topic for research on learning processes.

4.2.4 Concept formation and conceptual development

Learning is not just learning of facts but, more importantly (as was argued in section 3.3), learning of structures that enhance understanding. A particularly important area concerns how concepts are learnt and how they develop over time in the mind of an individual (or in a group). This is an area where results from research in many areas should be tied together. Consequently, interdisciplinary work will really be necessary. Much of this work is also carried out in educational settings.

Among the research proposals that we have received, one finds several that relates to the area of concept learning and conceptual development. Again, it is

impossible to give an overview of all of them, but we just briefly present a few of the proposals.

Helge Strömdahl proposes a project concerning conceptual change in science and technology education. Combining ideas from Piaget's theories of knowledge formation and Kuhn's paradigm shifts, there seems to be a lively development of theories in the area that can form the basis for experimental research on different educational programs.

Lennart Lundberg, Martin Stigmar and Simon Winter want to investigate the role of conceptual hierarchies in ICT tools. Students often have problems in "lifting" their knowledge to higher levels of abstraction and representations of conceptual hierarchies in ICT contexts may ameliorate this and also improve the meta-cognitive awareness of the students. A related project is proposed by Mina O'Dowd who wants to study concept formation via different representational practices and representational techniques.

Nils Dahlbäck focuses on learning styles in his proposal. In principle, ICT tools for learning can be adapted to the learning styles of different individuals. In practice, however, this is rarely used. Dahlbäck wants to study the relationship between learning styles and different knowledge types. His research fits well with that of Agneta Gulz.

In their proposal, Jussi Karlgren and Magnus Sahlgren want to model language acquisition, which is a central case of conceptual development. Successful models of language learning not only help us understand how children do it, but are also important for the development of autonomous language learning systems.

The proposal by Mikael Johannesson is of a more foundational character, focusing on the integrality vs. separability of the conceptual dimension that are extracted when individual learn to categorize perceptual information. Even though the empirical basis for this research comes from humans, it has immediate application for the design of the conceptual structure in computer based information systems and for machine learning.

Apart from these projects also the proposals by NAIL (Network for Analysis of Interaction and Learning by Berner Lindström and Oskar Lindvall), Thomas Lingefjärd, Måns Holgersson, Mikael Alexandersson and Louise Limberg, Sven Andersson and Ingrid Andersson fall under the general heading of research on conceptual development inside as well as outside educational practices. Again, this strongly motivates the topic as one of the central in our proposal.

As should be clear, the proposal in this subsection can lead to research that will generate new educational practices or improve the scientific grounding for existing ones.

4.2.5 Intersubjectivity and dialogue: consequences for meta-cognition, social learning and communication

The fourth topic that we suggest is not quite as coherent a research area as the previous ones. However, there is a field of questions concerning the fundamental cognitive functions related to an individual's understanding of the thinking of others (and of her own thinking) that do not fall directly under education science or pedagogy, but are obviously highly relevant for these.

Several proposals directly or indirectly concern the role of dialogues in learning. Since Vygotsky's socio-cultural perspective on learning was introduced, the role of group interaction and other social factors for individual learning have come

into focus, in particular his notion of the ”zone of proximal development”. And as was argued in section 3.4 much of organizational learning boils down to learning in dialogue settings. However, the mechanisms for this kind of learning require considerable further research and they should optimally be grounded in neuroscience or cognitive psychology.

Among the proposals on the role of dialogues for learning, one can mention that of Gunilla Svingby, Anders Jakobsson and Claes Malmberg who want to study dialogue learning in net based applications and that of Isak Benyamine, Cecilia Katzeff and Jin Kjölberg from the Interactive Institute who want to focus on the role of sharing, reflection and artefacts in dialogues. Another example is the NAIL group that focuses on how interactive learners create common meanings and actions by studying the communication that leads to the establishment of practices. Yet another is the proposal by Lauritz Brännström and Stefan Jern who want to analyse how and when groups of learners can become more efficient problem solvers. However, there are several other proposals that relates to studies of dialogues.

As described in section 3.3, it has been discovered recently that the metacognition of learners, i.e. their ability to reflect on and assess their own learning, is a factor that strongly correlates with the efficiency of the learning. This research area is still in its infancy and much more knowledge about different kinds of metacognition and the mechanisms whereby it affects learning is needed. Among the research proposals, there are several that touch upon metacognitive issues. The clearest example is the proposal by Nikos Mattheos and Rolf Attström who want to study students' self-assessment ability, how it can be enhanced, and how it affects the learning of the students.

One research field that runs across several of the fields presented in section 3 is learning processes in people with different kinds of disabilities. This is an area that is of great importance for the proposed programme and several of the research proposals we have received have clear implications for disability and learning.

In the present context, the proposal of Jerker Rönnberg and his group in Linköping is particularly interesting. Their general approach is to study how individual cognitive abilities contribute to communicative and social compensation and to investigate this in relation to alternative and augmentative communication. The approach compares persons with different kinds of communicative disabilities with those who use a different means of communication, artificial or natural. Apart from evaluations of communicative competencies, investigations into possible limitations of the ”theory of mind” of the disabled, i.e. their ability to understand the thoughts of others, becomes a focus of the research.

This form of disability research may be viewed as a method of studying how far the limits of human potential for learning and compensation can be stretched. Further knowledge of these limits will teach us a lot about the mechanisms of normal learning, cognition and communication.

Apart from the proposals mentioned above, those by Jarl Backman as well as Iréne Johansson, Anders Nilsson and John Sören Pettersson also fall under the general heading of this section. The strongly interrelated topics of intersubjectivity (“theory of mind”), meta-cognition, social learning and communication form a quickly developing research area where education science can fruitfully be supported by results and ideas from cognitive science, psychology, linguistics and

disability research. Again, the proposals indicate that Swedish research groups have a good potential for making substantial contributions to this genuinely cross-disciplinary field.

4.2.6 Additional fields

As can be seen from the survey above, the five focus fields that we have identified cover the topics of most of the research proposal that we have received. There are very promising possibilities for creating new constellations of research groups that work on closely related research areas, but who attack it from the background of different disciplines. A new research programme for learning processes would provide the nourishment that is needed to make such interdisciplinary research thrive.

Many of the proposals that we have received are concerned with topics that are connected with more traditional pedagogy or educational science. Since our questionnaire was not directly focused on these areas, there are many qualified researchers who did not show up in our collection, but who already are active in research in the area. Some of these projects are funded by the Committee for Educational Science of the Swedish Research Council, the Council for the Renewal of Higher Education and by The Bank of Sweden Tercentenary Foundation..

However, there are some proposals that we have found difficult to sort under the four headings above, but that we still would like to mention in the present context as examples of potentially interesting research. The one by Leonard Ngaosuvan concerns the role of interactive novels in educational materials. The objective is to investigate the possibilities to utilize the motivational factors that interactive novels can bring into learning material. Another related proposal by Lone Malmborg, Micke Svedemar och Pelle Ehn is about computer game worlds as learning environments. This proposal focuses on the social interactions that can take place in such games and how they can foster learning. Finally, the proposal from Pelle Ehn and the Creative Environments group in Malmö concerns how the physical environment can be enhanced by techniques from augmented reality, ubiquitous computing and ambient environments in such a way that different kinds of learning are enhanced.

5. The US National Research Council report, the OECD report and some other international initiatives

After this survey of the main themes of research on learning processes and the central future research question we have identified, we now turn to a brief presentation of some related international initiatives. It has not been possible to make a comprehensive survey, but we confine ourselves to a few that come close – in content or in geography – to the one we advocate.

The National Research Council in the USA appointed a "Committee on Developments in the Sciences of Learning" lead by John D. Bransford and Ann L. Brown. They presented their work in 1999 in the form of a book with the title *How People Learn: Brain, Mind, Experience and School*. Even though their focus is more on learning in schools than is the case in the present report and their target is the American educational system, there are many similarities between the report from the committee and the current one. The book can be read as a good source of material about current research on learning processes.

The committee concludes by a number of recommendations. There is a great deal of overlap between these recommendations and the ones proposed in the present

report. Here we will only mention the conclusions of the committee concerning strengthening the research foundations of the learning sciences (pp. 236-237). They recommend

- a commitment to basic research programs in cognition, learning and teaching.
- establishing new research programs in emerging areas, including technology, neurocognition, and socio-cultural factors that mediate learning. Research is needed on the interrelations between learning and learning environments and between teaching and learning.
- new assessment research to focus on improving and implementing formative assessments.

In 2002, OECD published a report on *Understanding the Brain: Towards a New Learning Science*. Its goal is to show how brain science may be relevant to educational policies. The overall focus of the report is on how results from neuroscience can generate recommendations for how learning environments and learning agenda should be designed for children, in particular young children. In particular they consider intensive early training programmes in numeracy and literacy and how dyslexia and dyscalculia can be remedied. Another central theme is the role of sensitive periods in the development of the brain and the possible consequence for an age-related curriculum of learning.

The report takes as its starting point the following ten questions (see pp. 11-14):

1. What is the balance between nature and nurture in the promotion of successful learning?
2. How important are the early years to successful lifelong learning?
3. How significant is the distinction between "natural development" and "cultural education"?
4. If the distinction is significant, how can we best promise these two types of learning - between "natural development" and "cultural education"?
5. How far is the successful learning of specific attitudes, skills and knowledge age-related?
6. Why is remedial education so difficult?
7. What can be said about different "styles of learning"?
8. What is intelligence?
9. What is emotional intelligence?
10. How does motivation work?

The OECD report focuses on individual learning. This is a bit narrower than the scope of the present proposal, but the report nevertheless serves as a good comparison and a source of material. One drawback of the OECD report is that it follows the current fashion within neuroscience to focus on brain imaging. The different techniques for brain imaging like PET, fMRI, etc, are marvellous tools for our understanding of how the brain functions and given the rapid development of these techniques, we will learn even more from brain imaging in the future. Nevertheless, it should be kept in mind that neuroscience provides us with many other techniques for studying the brain that may give us answers of a different kind from those generated from brain imaging research. In general, brain imaging

provides us with information about the brain on a rather coarse physical scale and limiting temporal resolution (even though the scales are rapidly getting finer). And for many of the problems areas related to learning processes, this scale is just not sufficient. For example, when investigating the results of different kinds of training programs, when learning a motor skill or when learning to read, one has to fall back on other techniques to understand what is changing in the brain.

Given our broader perspective that includes the learning brain and the learning organisation, the following general questions, distilled from the discussions in section 3, also become relevant:

- How is learning in single synapses and neurons (i.e. LTP/LTD) related to learning in neuron assemblies and learning in an individual (brain)?
- How do emotions, happiness, fear, rewards and punishments influence and control learning?
- How can machine learning and human learning be compared?
- What is understanding? How can it be promoted?
- What are the consequences of the current development in digital technologies and media for human learning and for the nature of our knowledge?
- How can learning in organisations be understood and identified? What are the differences in comparison with individual learning?

In 2002, OECD also published a report from the Neuroinformatics Working Group that has developed findings and recommendations on cooperation in the discipline that combines neuroscience and the information sciences. The report focuses on the issues of computational resources, guidelines and ontologies for data-sharing, and funding mechanisms.

In the US, there are many other initiatives concerning research on learning, in particular in relation to the use of ICT in education. To give but two examples, one can mention the Learning Research and Development Center at University of Pittsburgh, led by Lauren Resnick, and Stanford Learning Lab, led by Roy Pea.

In 1997, the Japanese government initiated an ambitious and long-term (20 years) program on brain research. The initiative focuses on three areas: (1) understanding the brain, (2) protecting the brain, and (3) creating the brain. Although the Japanese program does not directly focus on learning processes, there are several areas of overlap with the programme proposed here. If the proposed Swedish programme will be established, it would clearly be of mutual benefit to both countries to try to coordinate the research plans of the two programmes.

In the United Kingdom there is an extensive research programme in education Teaching and Learning Research Programme (TLRP). TLRP is funded by ESRC, the major funding agency in the social sciences, and was instituted to stimulate research on teaching and learning in education, and to create closer links between research and schools.

The Dutch Research Council NWO supports the Programming Council for Educational Research PROO that focuses on ICT in education. The role of this program seems similar to that of the Committee for Educational Science of the Swedish Research Council, albeit that the research area of the Dutch initiative is narrower.

In Denmark a Pedagogical University was created in 2000. It consists mainly of a fusion of three more traditional pedagogical institutions (Danmarks Lærerhøjskole, Danmarks Pædagogiske Institut and Danmarks Pædagoghøjskole). However, what makes the Danish Pedagogical University more interesting from the perspective of the present proposal is that Learning Lab Denmark has also been made part of it. Learning Lab Denmark is similar to the Interactive Institute in Sweden in its conception, although it focuses on learning. It is organized around research consortia with the following themes: Mathematics and Science; Neuroscience, Cognition and Learning; Play and Learning; The Creative Alliance; Tools for the Knowledge-Based Organisation; and Workplace Learning. It is obvious that there is a considerable overlap in content between these research themes and the ones proposed here. Learning Lab Denmark has just started up its research activities. Collaboration with activities in line with the proposed programme would be beneficial for both partners and it would contribute to achieving a critical mass within several of the subareas of research.

Norway has initiated a network for IT-Research and Competence in Education (ITU) that is a part of the Faculty of Education, at the University of Oslo. The establishment of ITU is one of the measures taken by the Ministry of Education in 2000-2003, to strengthen R&D in the pedagogical use of ICT in education. ITU shall acquire and transfer knowledge on how IT can be implemented and what opportunities IT provides for the promotion of learning and development on the part of the students and teachers in primary and secondary schools and teacher education. Thus there is some overlap with the present proposal, but it is considerably narrower and more directed towards applications. In Norway one also finds the KUL ("Kultur, utdanning, laering") programme that focuses on issues of learning in a rather broad sense. The projects include specific studies of teaching and learning in various areas (for instance, mathematics), the use of ICT in education, and many other activities.

In Finland, a cross-disciplinary research centre called CICERO that focuses on learning is currently planned at the University of Helsinki. The target of the research to be made in the research centre is learning in different forms, its conceptual understanding and empirical research. The emphasis is on basic research. The targets of the research in the centre cross the lines of individual science and its researches can't be effectively promoted within traditional subjects. The Academy of Finland sponsors an extensive research programme called Life as learning. The purpose of this activity is to promote an interest in issues of learning in all sectors of society, and in particular to promote interdisciplinary cooperation among scholars of different backgrounds.

The Swedish Learning Lab (SweLL), funded by the Knut and Alice Wallenberg Foundation. is a joint venture between Uppsala University, Karolinska Institutet, and the Royal Institute of Technology (KTH) in Sweden, each of which has its own local learning lab. SweLL was established in 1999 in order to initiate and co-ordinate projects that contribute to the advancement of computer supported learning in higher education. The labs also have close cooperation with the Stanford Learning Lab, USA, and Learning Lab Lower Saxony, Germany.

Even though there is a certain overlap between SweLL and the proposed program, the research conducted in SweLL is focused on computer-supported learning and more on practical implementation, while the program proposed here is broader and concerns primarily basic research. Thus the two initiatives would complement each other nicely.

6. Proposal

In section 3 we have presented an outline of the main research areas related to learning processes and on the basis of the project proposals received we have in section 4 identified a number of research themes that are particularly well suited for the Swedish academic scene. We have focused on research areas that are not already covered by funding agencies. *In summary, we propose that Swedish funding agencies join efforts in creating a research programme devoted to research on learning processes that bridges traditional disciplinary borders*.

The main goal of this report has been to argue that such work has the best potential for forwarding our knowledge about learning processes and to help creating new practical applications in education and other areas. A major reason for creating an interdisciplinary research programme is that, given the structure of Swedish research funding, it is otherwise difficult to find appropriate resources for this kind of bridging research.

We propose that an interdisciplinary research programme be focused on the following five main topics:

1. Synaptic, cellular and network mechanisms of learning and memory

Research in this area is not just experimental, but also modelling is a central activity. It builds on collaboration between several disciplines. Some of the main questions we have identified above are:

• Which are the sensitive periods in the development of the brain for various skills, for example, language learning? What changes occur in the brain when the learner leaves the sensitive period?

• What is the most adequate way of quantitatively describing the dynamics of the brain's memory networks in memory encoding and recall? What is the interplay between attention, working memory and long-term memory?

• Based on modern concepts of action planning and control, what is the most adequate way of optimizing relearning after neural injury and how does this way relate to type of injury? Research should seek to obtain basic knowledge that will lead to development of novel methods and designs for re-learning protocols tailored to the individual patient for achievement of optimal results.

2. The role of emotion and motivation in learning and memory

One of the current main trends in neuroscientific modelling of learning is that the learning mechanism cannot be separated from the *motivational* or *evaluative* aspects of these processes. As argued in section 3.1, this is as area where one finds large lacunas in our knowledge. To an even greater extent than the previous topic, this is an area that may have far-reaching consequence for the design of education. Some of the main questions in this field are:

• Although positive emotions are more interesting than negative ones from a general learning perspective, much less effort has been devoted to studying positive emotions such as joy than negative ones such as fear or anger. For example, does evaluative conditioning depend on the reward system? When participants learn to solve specific types of problems, do successful solutions activate the reward system, and is this activation directly related to the learning of problem solving skills?

• Using different methods to induce positive emotion, it has been demonstrated that participants perform better in a wide variety of tasks, including learning

tasks. The question whether happy students learn better than unhappy ones can be addressed at many levels, from basic experiments seeking to delineate neural mechanisms behind the effects of positive mood, to examining relationships between personality traits such as extraversion, mood, and learning, and to looking at the effect of emotional climate in classrooms.

3. Concept formation and conceptual development

The development of the knowledge of an individual is not entirely cumulative, but one sometimes has to revise one's conceptual system. However, early mistakes in concept formation have a tendency to stick to ones thinking. Some of the main questions in this field are:

• How are concepts are handled in the brain? We need substantial research to find out what constraints neuroscience puts on theories of concept formation.

• Education often involves negotiations of partially understood concepts. We need to know how this negotiation functions. A related question is: how do group processes of concept learning function?

• Children are building knowledge all the time in their everyday activities inside and outside formal institutions. How does it work? How much does education influence the constructions? What is the relationship between learning in formal settings and other contexts?

• How much does language influence concept formation (in childhood as well as in adults)?

4. Intersubjectivity and dialogue in contexts of teaching and learning

Again, this is an area where one finds large gaps in our knowledge, both on the conceptual and on the factual levels. Research in this area will improve our understanding of meta-cognition, social learning and communication. In this way it will contribute to the foundations of organisational learning. One particular topic is how ICT will influence intersubjectivity and dialogue. Some of the main questions we have identified above are:

• Recent theories of language learning emphasise that children exploit that fact that speakers have *intentions* to communicate when they speak Thus language learning and concept formation depend on children achieving intersubjectivity and having a so-called "theory of mind", i.e. that they understand the emotions, intentions and beliefs of others. How can we make the methods for determining children's theories of mind more operational?

• How does intersubjectivity of meaning become established in learning situations? The ability to achieve shared reference (joint attention) is necessary for this).

• How does metacognition influence affective aspects of learning? How do metacognitive processes develop in relation to cognitive ones, and vice versa?

• How do ICT and ensuing changes in media use affect communicative practices in formal education?

5. Computational modelling

This topic runs across all of the four previous fields because computational modelling is relevant for all levels of learning. This theme will also have consequences for the creation of artificial learning agents. Some of the main questions in this field are:

• How can knowledge about the dynamics and modulation of synaptic plasticity and neuronal properties embodied in computational models be related to phenomenological learning processes?

• How can we use computational models of neuronal and synaptic learning processes in the design of computer based technology for learning, diagnosis and therapy of attention and memory disorders and deficits in the young and the elderly?

• Can the design and study of artificial brain-inspired learning and acting systems tell us something about the nature of and interaction between the corresponding biological functions?

To be sure, one already finds research on these five areas in Sweden, but the projects tend to be on a rather small scale and pursued from the perspective of one traditional discipline only.

Since interdisciplinary work based on these themes, which we believe is needed for rapid progress in research on learning processes, would cross organisational funding boundaries and thus may have difficulties in being funded in spite of promise and quality, this motivates a pioneering effort to create a separately funded programme for the suggested themes.

We believe further that resources should be made available for a comparatively long-term programme as it takes long time to build up interdisciplinary research and break new ground. Evidently this work must be undertaken in close collaboration with groups in other Nordic countries, with European groups and other international research groups. Evidently there is a growing interest internationally for this field of research and Sweden seems to be well placed to play an important role in many areas of work.

A very minimum is that the projects within the programme are allowed to run over at least five years in order to allow for a generation of Ph.D. students to complete their theses within a project. However, it is at least as important to create funding for post-docs, and senior researchers (lecturers and professors). The creation of an active network in Sweden of researchers from different disciplines on learning processes should be an outcome of the programme.

Another option that may be considered is to provide funding for graduate schools ("forskarskolor") for Ph.D. students. In such an environment, Ph.D. students, who may have their basic education in different disciplines related to learning processes, may meet with a group of supervisors and teachers that will place the post-graduate work of the students directly in an interdisciplinary research environment. Such a school may be en excellent way of fostering the next generation of researchers within the area of learning processes.

References

Argyris, C. (1992). On Organizational Learning. Oxford: Blackwell.

Bliss, J., Säljö, R., and Light, P. (Eds.). (1999). Learning Sites: Social and Technological Resources for Learning. Oxford: Pergamon.

Bloom, P. (2000). How Children Learn the Meaning of Words. Cambridge, M.A.: MIT Press.

Bohm, D. (1996). On dialogue. In L. Nichol (Ed.) On Dialogue. London: Routledge.

Bransford, J. D., Brown, A. L., and Cocking, R. R. (Eds.). (1999). How People Learn: Brain, Mind, Experience, and School. Washington, D.C.: National Academy Press.

Caianiello, E. (1961). Outline of a theory of thought-processes and thinking machines. Journal of Theoretical Biology 1: 204-235.

Churchland, P. S., and Sejnowski, T. J. (1994). The Computational Brain. Cambridge, M.A.: MIT Press.

Damasio, A. (1994). Descartes' Error: Emotion, Reason, and the Human Brain. New York: GP Putnam's Sons.

Davidson, J. E., and Sternberg, R. J. (1998). How metacognition helps problem solving. In D.Hacker, J. Dunlosky and A. Graesser. Metacognition in Educational Theory and Practice. Mahwah, N.J.: Lawrence Erlbaum Associates.

Eklund, H. (1995). Pedagogisk forskning under en femårsperiod. En studie av innehåll och forskningsmönster i svenska doktorsavhandlingar under åren 1988-1992. Institutionen för pedagogik och psykologi, Linköpings Universitet.

Eklund, H. (2000). Svenska doktorsavhandlingar i pedagogikåren 1993-1997. Ämnesområden och forskningsmönster. En uppföljningsstudie. Institutionen för pedagogik och psykologi, Linköpings Universitet.

Gee, J. P., Hull, G., and Lankshear, C. (1996). The new work order. Behind the language of the new capitalism. St Leonards, Australia: Allen & Unwin .

Gulz, A. (1999). "Does one size fit all?" – kognitiv variation och IT. Human IT, 2 (99), 61-73.

Gärdenfors, P., and Johansson, P. (Eds.). (To appear). Cognition, Education and Communication Technology. Mahwah, N.J.: Lawrence Erlbaum Associates,

Gerstner, W. (1999). Spiking neurons.In W. Maass and C. Bishop (Eds.) Pulsed Neural Networks. Cambridge, M-A.: MIT-Press

Gopnik, A., and Meltzoff, A. N. (1997). Words, Thoughts, and Theories. Cambridge, M.A.: MIT Press

Hall, L. (2003). Self-Knowledge/Self-Regulation/Self-Control: A Ubiquitous Computing Perspective. Lund: Lund University Cognitive Studies.

Haykin, S. (1998). Neural Networks: A Comprehensive Foundation. Upper Saddle River, N.J.: Prentice Hall.

Jonassen, D. (2000). Computers as Mindtools for Schools: Engaging Critical Thinking. Upper Saddle River, N.J.: Merrill.

Koch, C., and Segev, I. (Eds.). (1998). Methods in Neuronal Modeling: From Ions to Networks. Cambridge, M.A.: MIT Press.

Koschmann, T. (Ed.) (1996). CSCL: Theory and Practice of an Emerging Paradigm. Mahwah, N.J.: Lawrence Erlbaum.

Pressley, M. (1994). Embracing the complexity of individual differences in cognition: Studying good information processing and how it might develop. Learning and Individual Differences, 6, 259-284.

Pulvermüller, F. (2001), Brains reflections of words and their meanings. Trends in Cognitive Science, vol. 5, no. 12, 512-524.

Rolls, E., and Treves, A. (1997). Neural Networks and Brain Function. Oxford: Oxford University Press.

Scott, A. C. (2002). Neuroscience. A Mathematical Primer. New York: Springer-Verlag.

Senge, P. (1990). The Fifth Discipline: The Art and Practice of the Learning Organisation. London: Century.

Skinner, B. F. (1965). Science and Human Behavior. New York : Free Press.

Sternberg, R. (1997). Thinking Styles. Cambridge, M.A.: Cambridge University Press.

Tomasello, M. (1999). The Cultural Origins of Human Cognition. Cambridge, M.A.: Harvard Unversity Press.

Vosniadou, S. (1994). Capturing and modeling the process of conceptual change. Learning and Instruction, 12, 3, pp 235-275.

Wasson, B., Ludvigsen, S., and Hoppe, U. (2003). Designing for Change in Networked Learning Environments. Dordrecht: Kluwer Academic Publishers.

Wooldridge, M. and Jennings, N. R. (1995). Agent Theories, Architectures, and Languages: a Survey. In M. Wooldridge and N.R. Jennings (Eds.). Intelligent Agents. Berlin: Springer-Verlag.